




Review on visualization technology in simulation training system for major natural disasters

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Received: 10 October 2021 / Accepted: 27 January 2022 / Published online: 16 March 2022
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Abstract

Major natural disasters have occurred frequently in the last few years, resulting in increased loss of life and economic damage. Most emergency responders do not have first-hand experience with major natural disasters, and thus, there is an urgent need for pre-disaster training. Due to the scenes unreality of traditional emergency drills, the failure to appeal to the target audience and the novel coronavirus pandemic, people are forced to maintain safe social distancing. Therefore, it is difficult to carry out transregional or transnational emergency drills in many countries under the lockdown. There is an increasing demand for simulation training systems that use virtual reality, augmented reality, and mixed reality visualization technologies to simulate major natural disasters. The simulation training system related to natural disasters provides a new way for popular emergency avoidance science education and emergency rescue personnel to master work responsibilities and improve emergency response capabilities. However, to our knowledge, there is no overview of the simulation training system for major natural disasters. Hence, this paper uncovers the visualization techniques commonly used in simulation training systems, and compares, analyses and summarizes the architecture and functions of the existing simulation training systems for different emergency phases of common natural disasters. In addition, the limitations of the existing simulation training system in practical applications and future development directions are discussed to provide reference for relevant researchers to better understand the modern simulation training system.

Keywords Simulation training system · Visualization technology · Major natural disasters · Emergency drill

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1 Introduction

In the past few decades, global natural disasters have occurred frequently, claiming millions of lives, adversely affecting the lives of more than 1 billion people, and causing heavy economic losses (Wang 2012; Watson et al. 2007; Yang et al. 2014). Major natural disasters are usually extreme events in nature originating from the atmosphere, geology, and hydrology, with unpredictable characteristics (Wang 2012; Watson et al. 2007; Yang et al. 2014). Faced with sudden and major natural disasters, most emergency rescue personnel rarely have the experience of dealing with such disasters. Additionally, the general public is even less aware of natural disasters and does not know how to better prevent, mitigate, prepare and provide disaster relief. Therefore, it is urgent to strengthen emergency drills to avoid or reduce the risk and harm caused by major natural disasters.

Emergency drills are a vital part of emergency management work. It is a necessary way to assess emergency plans, improve emergency preparedness, train commanders, and popularize science (Zhang et al. 2010). Emergency drills fall into two main categories: discussion-based exercises and operations-based exercises (Skryabina et al. 2017, 2020). Discussion-based exercises include seminars, workshops, tabletop exercises (TTXs), and games (Skryabina et al. 2020). Seminars are usually used to introduce relevant institutions, strategies, plans, policies, procedures, agreements, resources, or concepts and ideas to participants. Workshops are similar to seminars, but workshops increase the interaction between participants and focus on the implementation or construction of products such as plans and procedures. TTXs enable participants to practise their response and contingency plans through group discussions. In these scenarios, participants often sit face-to-face, verbally describe their actions, discuss and communicate to overcome the challenges posed by the exercise scenarios (van Laere and Lindblom 2019). Operations-based exercises include drills, functional exercises (FEs), and full-scale exercises (FSEs). They require investment in equipment, resources, and manpower. They usually last for a long time, but they can show the real reactions of the participants (Skryabina et al. 2017). The drill is an activity that requires coordination and control. It is normally used to train new equipment or maintain existing skills. FEs are mainly an activity to test and evaluate personal abilities (To et al. 2019). FSEs are the most complex exercise to test all or most of the functions, but they take a long time and have relatively limited opportunities for organization (Johan et al. 2013; Roud et al. 2020). Compared with the two types of exercises, discussion-based exercises usually focus on policy-oriented and strategic problems, while operations-based exercises focus more on tactical problems.

Unfortunately, these traditional forms of exercises have many shortcomings in terms of cost, implementation complexity, reproducibility, and agility (Evain et al. 2021). Meanwhile, due to the outbreak and continuation of the global novel coronavirus pandemic since December 2019 (COVID-19), many countries have been forced to adopt lockdown measures (such as reducing unnecessary movement of people or major events, etc.), urging people to maintain social distancing to curb the spread of the virus (Ashraf 2021; Ghosh et al. 2020; Koumaditis et al. 2021). This has brought many challenges to the development of transregional or transnational emergency drill cooperation (Ashraf 2021). Balancing the needs of social distancing and emergency drills has become a problem that plagues us. When attempting to solve these problems and overcome the established form of traditional exercises, simulation exercises based on visualization

technology seem to be more appealing and safe (Duan et al. 2019; Fei et al. 2013). At the same time, training people to be ready for the next major natural disasters through simulation exercises is an important issue.

In the last few years, with the improvement of computer hardware computing power and the development of display technology, visualization technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) have brought new visual feelings and interactive experiences to users. VR is the use of a computer-generated virtual environment to simulate the real world (Kumari and Polke 2019). AR superimposes the real environment and virtual objects on the same screen or space in real time, thereby enhancing the user's sense of realism (Dini and Mura 2015). In other words, AR technology is a combination of real reality and virtual reality. MR refers to the fusion of the real world and the virtual world, including AR and augmented virtuality (AV) (Flavián et al. 2019). Visualization technologies, such as VR, AR, and MR, have been used in simulation training systems in different fields, such as in military training (Alexander et al. 2017; Mao and Chen 2021), building safety (Moore and Gheisari 2019), education and training (Akçayır and Akçayır 2017; Englund et al. 2016; Nincarean et al. 2013), surgical simulation (Gallagher et al. 2005; Khor et al. 2016), and mental health treatment (Chicchi Giglioli et al. 2015; Riva and Serino 2020). The simulation training system using visualization technology can provide participants with a simulation training environment similar to the real situation. To a large extent, it has changed the arduous circumstances of conducting emergency drills due to restrictions, including high cost, time consumption, difficult organization, and limited scope (Caballero and Niguidula 2018). Therefore, the simulation training system based on visualization technology has become an important training tool for emergency drills of severe natural disasters. Scholars at home and abroad have carried out comprehensive research on various simulation training systems to address natural disasters (Gong et al. 2015; Schluse et al. 2015; Takeuchi 2005; Yu et al. 2016; Zhang et al. 2020, 2019). To the best of our knowledge, some literature has made considerable effort to review the major progress in the study of visualization technology for security. It should be noted that these reviews are not exhaustive. Moreover, thus far, these reviews are limited visualization technology in the construction industry, for surgeries, and in other fields, as well. There has not been such a review on natural disaster simulation exercise training. The frequent occurrence of various natural disasters around the world in the last few years, especially during the outbreak of COVID-19, has forced movement of people to be greatly restricted. Thus, in this context, this paper reviews and summarizes the more widely used visualization technology and systematically sorts out and summarizes the simulation training system using visualization technology for the different emergency phases of common natural disasters. This work further compares and analyses the functions, architecture, and limitations of visualization technology and proposes suggestions to improve and develop simulation training systems in the future. In addition, it is worth noting that most current simulation training systems are usually only provided for a small number of trainees. There is less data support for the effectiveness of the simulation training system in the actual disaster emergency response. There is still opportunity further research on the large-scale promotion and application of simulation training systems for major natural disasters in the future.

The rest of the paper is organized as follows: Sect. 2 introduces the literature retrieval method. Section 3 describes the development of the deduction system. Section 4 introduces the types of visualization techniques applied in the simulation training system. Section 5 shows some simulation training systems and their system architecture and functions that are applicable to the four major phases of natural disaster mitigation, preparedness, response, and recovery. Section 6 discusses some shortcomings of simulation training

systems in practical applications. Finally, Sect. 7 summarizes the full text and proposes an outlook for future research directions.

2 Literature search methods

We conduct a literature search to find existing simulation training systems for natural disasters. The datasets used in this paper are from the core collection of Web of Science (WoS), Elsevier Science Direct, Springer, and China National Knowledge Infrastructure (CNKI). Before searching for keywords, we establish a certain inclusion basis to design a clearer boundary for the literature search. The four main grounds for inclusion are as follows. First, the candidate publication studies natural disasters. Second, the concepts of commonly used visualization technologies and the relationships between related technologies are included. Third, the goal of the thesis is to sort out the simulation training system designed for natural disaster prevention or emergency response. Fourth, the shortcomings of the existing simulation training system are discovered and suggestions for improvement are proposed. The search task involves retrieving various terms related to natural disasters and simulation training systems in publication abstracts, titles, and keywords. At the same time, we repeat the search task with synonyms or synonyms representing the same concept. For example, for the terms related to natural disaster, we search for “disaster”, “disaster risk”, “extreme event”, “earthquake”, “landslide”, “emergency”, “flood”, and “fire”. Similarly, for the simulation training system, we search for “simulation”, “training system”, “simulator”, “virtual reality”, “augmented reality”, etc. In summary, when we search for literature, we combine a word in List A with a word in List B, as shown in Table 1.

3 Development of the deduction system

In Military Dacihai, the term “deduction” is interpreted as an exercise carried out in military exercises in accordance with the sequence of exercise problems and the course of the possible development of the battle or combat. The research related to deduction includes sand-table simulation research, wargaming research, and emergency simulation training systems under various emergencies.

Table 1 Lists of keyword sets used during literature searching

List A	List B
Natural disaster	Simulator
Natural hazard	Simulation
Emergency drill	System
Emergency exercise	Drilling system
Disaster risk	Training system
Disaster management	Simulation system
Extreme events	Virtual
Flood	Virtual reality
Earthquake	Augmented reality
Fire	Mixed reality

The sand-table originated from a small game that was used as both a military tool and for entertainment. It was first used in the military (Smith 2009). Wood or stone marks were set on the sand to simulate the state of the war and interpret the upcoming war. The red and blue armies achieved the goal of discovering the strategic and tactical problems of the two sides and improved their commanders' combat capabilities through confrontation and competition on the battlefield. Sand-table simulation effectively avoided the enormous cost and time-space obstacles in military practical exercise. Well-known business schools and management consulting organizations in the United Kingdom and the USA realized that military sand-table simulation is also suitable for training the middle and high-level managers of enterprises. They finally developed a new modern training model of a sand-table actual combat simulation for a corporate environment (Xi et al. 2016). Due to the frequent occurrence and complexity of power grid accidents in the last few years, Xi et al. (2016) designed a construction plan for a "bulk power system sand-table simulation system" based on the existing dispatch automation system. They also built a demonstration system in the Central China Power Grid. It is an efficient and intelligent analysis platform for the safety and stability of the power sector. Finally, decision support, such as scheduling, planning, and method formulation, was provided.

Wargaming is a kind of war simulation method where personnel on the opposing parties make decisions and determine the consequences of the decision according to some rules. Wargame has a long history as a critical tool for military training, education and research (Saković et al. 2019). The word "wargame" comes from the German word "Kriegsspiel". In comparison with the sand-table, its advancement lies in replacing sand with paper and adding rules ensuring that the exerciser makes some predictions in a rough virtual space (Chen et al. 1999). Wargaming has been widely used in major wars, and the drill effects have been exceedingly effective in World War II. After World War II, wargaming was still used in military training by the USA and was considered to be the vanguard of the development of military wargaming in the twentieth century (Schwarz 2013). In 1995, Campion (Campion 1995) discussed the computerisation of wargaming in the mid-1950s. In the same year, the RAND Corporation of the USA designed a simulation exercise for their country's air force logistics system. Participants were required to act as inventory managers in the simulation of the Air Force supply department (Faria et al. 2008).

With the increasing development and improvement of wargaming concepts, scientific theoretical methods, computer information technology, and performance, heightening the simulator's ability to respond in time and make active decisions during exercise tasks has become an important study direction for researchers. For this reason, building an emergency simulation training system under various common disasters by means of simulation technology has gradually become a research hot spot in the last few years.

4 Visualization technology applied in simulation training systems

With the continual improvement of computer technology, VR, AR, AV, MR, and other new visualization technologies are constantly added to the deduction process, which provides people with the opportunity to set up various emergency environmental variables. With these new visualization technologies, trainees can face actual threats in a virtual environment while being safe from danger themselves.

Jaron Lanier, the founder of the American VPL company, coined the term VR in 1989 (Lele 2011). VR is a three-dimensional virtual world (Illusion) generated by

computer simulation, which makes users feel as if they are on the scene (Immersion) (Vles et al. 2020). It continues to develop with the birth of modern computer technology. A paper entitled “Ultimate Display” was published by Sutherland in 1965 (Sutherland 1965). He proposed a new theory of human–machine interaction, including the use of a certain dialogue language between humans and computers. This certain type of interaction depicted a complete information exchange between humans and computers. This theory was mainly characterized by real feelings and interactions. In addition, he also described a new display technology in the paper. Using this technology, users would be directly immersed in a computer-controlled virtual environment and interact with objects in the virtual environment in a natural way (Interactivity). In 1968, Sutherland (1968) successfully invented the head-mounted 3D display (HMD), which is considered the first VR device (Sutherland 1965). It is also generally considered to be the prototype of augmented reality and head-mounted display equipment. Additionally, it was able to convert simple line diagrams into 3D images. However, at this time, there was no term called “Augmented Reality (AR)”.

Until 1990, Caudell and Mizell (1992), a researcher at the broadcasting company, officially proposed the term “Augmented Reality”. AR is the second step after virtual reality, which seamlessly superimposes computer-generated virtual objects or images in the actual world (Dey et al. 2018; Yim et al. 2017). The integration of the virtual world with the actual world not only increases the user’s perception of the actual world (Liveness) (Syberfeldt et al. 2017) but also enhances the effect of actual environment presentation through virtual objects (Enhancement) (Milgram and Kishino 1994). Compared with VR, AR focuses on the actual world rather than an entirely artificial environment (Barsom et al. 2016), while VR achieves complete virtualization by creating a completely artificial environment (Buhl et al. 2009). Through hand-held devices (tablets, smartphones), head-worn displays (Perspective Glasses), spatial equipment (projectors), and other carriers (Fast-Berglund et al. 2018; Syberfeldt et al. 2017; Vles et al. 2020), to express an enhanced sense of reality, users will perceive the virtual content is consistent with the objects in the real world (Relevance) (Hanna et al. 2018). Then, users can interact with virtual objects in reality through AR and experience a real presence (Barsom et al. 2016), which is the progress made by VR. Currently, AR is usually used for medical treatment, education, and corporate training, aiming to improve the perceptibility of situational awareness in training courses (Barsom et al. 2016). Moreover, its procedures chiefly have the following three characteristics (Azuma 1997; Ruger et al. 2020): (1) The presentation of scenes and information overlaps with reality; (2) virtual objects are linked to reality spatially; and (3) they have interactive capabilities. With the technological advancement of mobile devices, such as smartphones, mobile augmented reality has become increasingly popular in the last few years. It is especially suitable for people who need information support when focusing on a certain task. With the potential of VR, people can interact with computer-supported information (which may be real-time feedback from remote experts or databases) without being disturbed by the actual world. It has the potential to enable people to interact with computer-supported information (perhaps from a database or real-time feedback from a remote expert) without being distracted from the actual world around them. It is achievable for those who want to control the computer but also want to do other things.

In addition, another term, AV is easily confused with AR. Both AR and AV have a common goal of enhancing the actual world with virtual information. The difference between the two terms is that AV maps some images or videos of the actual world to virtual objects (Tamura et al. 2001; Valente et al. 2016), and AR adds virtual information to physical reality, thereby enriching the actual world (Cabero and Barroso 2016).

Visualization Type	Virtual Reality (VR)	Augmented Reality (AR)	Mixed Reality (MR)
Explanation	“A sheer fabrication out of nothing”: Everything you see is a virtual illusion.	“Icing on the cake”: You can see both the real world and virtual things.	“Real and Illusion Intertwined”: It is difficult to distinguish whether what you see is real or simulated.
Features	<ul style="list-style-type: none"> ■ Immersion ■ Interactivity ■ Illusion 	<ul style="list-style-type: none"> ■ Liveness ■ Enrichment ■ Relevance 	<ul style="list-style-type: none"> ■ Liveness ■ Blend ■ Realism

Fig. 1 The relationship and characteristics of VR, AR, and MR

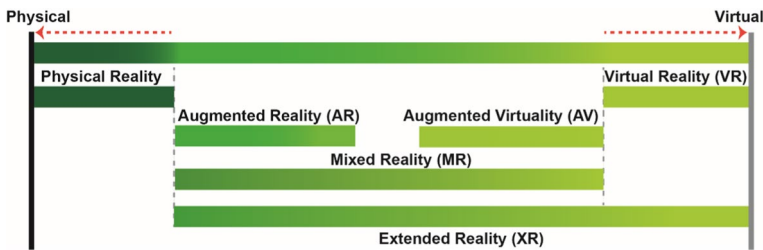


Fig. 2 The relationship between the five terms AR, AV, MR, VR, and XR

MR generally refers to the blend of the actual and virtual worlds (Liveness, Blend) to generate new surroundings and visual images, enabling virtual and real objects to coexist and interact. MR is a broader term that encompasses augmented reality and augmented virtuality (Flavián et al. 2019). It is an extension of augmented reality technology and a further development of virtual reality technology. It has the characteristics, such as adding virtual information to real information and revealing real information in virtual information (Realism) (Fast-Berglund et al. 2018; Tecchia 2016). Compared with VR and AR, MR has a faster real-time interaction speed. Because MR can render three-dimensional images more comprehensively and specifically, it replaces the physical environment. Also, because of its great advantages in timeliness, it is now widely used for emergency and trauma treatment (Hu et al. 2019a). In short, the relationship and characteristics among VR, AR, and MR are as follows (Fig. 1).

In addition, the term extended reality (XR) has recently emerged. It is a general term of immersion technology. XR refers to the use of computer technology and wearable devices to complete various experiences in the fuzzy boundary between the real world and the virtual environment (Alizadehsalehi et al. 2020; Fast-Berglund et al. 2018; Doolani et al. 2020). It covers different types, including VR, AR, and MR technologies (Alizadehsalehi et al. 2020). In other words, XR is usually an umbrella term for these methods or a combination of them (Wohlgemant et al. 2020).

We present one of the relationship diagrams that can easily distinguish the terms AR, AV, MR, VR, and XR based on the “reality-virtuality continuum” proposed by Milgram (1994), Olsson (2011) and others (Fig. 2).

5 Simulation training systems based on different phases of emergency management

5.1 Mitigation and preparedness

5.1.1 Simulation training system suitable for landslide disaster

Landslides are a common natural disaster caused by external stimuli such as rainfall, earthquakes, and human activities (Andersson-Sköld et al. 2013; Dai et al. 2002; Ju et al. 2020), resulting in an expansion of shear stress or a decline in soil shear resistance, which easily occurs in mountainous areas (Arnone et al. 2011; Dai et al. 2002). It has the characteristics of rapidness, wide range and great destruction (Zhang et al. 2020). Due to various factors such as climate change, the rapid increase in landslides has become a severe constraint on urbanization and economic development (Haque et al. 2019).

Zhang et al. (2020) proposed a method for constructing personalized virtual landslide disaster environments based on knowledge graphs and deep neural networks. Among them, the knowledge graph is used to clarify complex domain knowledge and relationships, and the deep neural network can mine the features and semantic information contained in the knowledge graph. This method can set different visualization preferences and demand information for the kinds of landslide disaster objects involved (e.g. ordinary people, victims, rescue teams, and experts in the field of emergency) (Peng et al. 2018; Steichen et al. 2014). Relying on the above approach, they developed a prototype system. The system not only provides a visualization and an interactive analysis of basic geographic scenes but also has three functional modes (global mode, user mode, and query mode). This system framework has four main parts: a data layer, a computation layer, a service layer, and a presentation layer. It is valuable for multilevel simulation, analysis, and decision-making of landslide hazards. The system uses the landslide disaster that occurred in Xiaogangjian, Sichuan Province, China on January 19, 2016 as a test case for experimental analysis. The experimental results show that the prototype system designed based on the construction method of a personalized virtual landslide disaster environment that depends on knowledge graphs and deep neural networks can intelligently recommend appropriate disaster information and scene data to different users. The accuracy is more than 80%, which can effectively support the construction of personalized virtual landslide disaster environments.

5.1.2 Simulation training system suitable for flood disaster

Floods, as a common natural disaster, have the characteristics of high frequency and prodigious destruction. Rainfall is generally the principal cause of flooding. However, flood is also affected by many other factors. Only early identification of weaknesses in flood control and reinforcement can effectively prevent floods and reduce economic losses. In the last few decades, due to climate change and rapid urbanization, the scale and frequency of flood disasters have increased substantially (Kousky 2012; Neumayer et al. 2014; Schumacher and Strobl 2011). Therefore, there is an urgent need for more dynamic prevention and decision-making tools.

Yuan et al. (2002) argued that the premise of flood routing simulation is to solve problems of computer visualization technology and even three-dimensional (3D) visualization simulation (Table 2). 3D visualization technologies, such as colour processing,

Table 2 Summarize the characteristics of the flood disaster simulation training system

Name of systems	Advantages	Disadvantages	References
Three-dimensional simulation system of flood routing	Diversified information presentation; Good user interface; Simple operation	Unreliable simulation process	Yuan et al. (2002)
Novel flood hazard warning system	Dynamic display; Real-time prediction	None noted	Wang et al. (2016)
Sponge city flood simulation and forecasting system	Good output expressiveness	Poor integration of different requirements visualization	Wang et al. (2019b)
GIS-based 3D visual simulation system for flood protecting	Good combination of information	None noted	Huang et al. (2006)
VE-based real-time interactive simulation framework	Faster system operation	More difficult and complex real-time simulation; Difficult operation changeability	Zhang et al. (2013)
Dynamic visual simulation and decision support system for flood risk management	Reduce decision time	Few types of models; Low operating efficiency	Wu et al. (2019)
Integrated virtual geographic environmental simulation framework	Break the static data-driven bottleneck	Cannot connect to information infrastructure	Ding et al. (2014)

light processing, texture mapping (sticking an image onto the surface of a three-dimensional object to make it more realistic), animation, fogging effects (mixing the colour of the scene with the colour of the fog according to the depth and distance of the scene, creating a three-dimensional scene closer to reality), transparency processing of watershed topography, river channels, and water bodies are the basis of simulation. The 3D flood routing simulation system studied by Yuan et al. has an immense lack in the reliability and usability. This is because it does not solve the problem of simulating the natural alluvial river flooding process. A novel flood hazard warning system proposed by Wang et al. (2016) not only simulates the flooding process by using the real world model and reconstructing the flood hazard warning environment, but also produces a simulation system interface suitable for decision-makers or users (Table 2). The early warning simulation system includes three subsystems: a 3D real world modelling system, a 3D environment reconstruction system, and a 3D flood simulation system. It can provide convenience for building a realistic urban environment, formulating flood control tasks and monitoring inundated areas. The new flood disaster warning system was used to conduct a flood simulation test in Tewkesbury, a small town in Gloucestershire, England that is often affected by floods. The results showed that the flood model based on the standard gradient descent method for energy minimisation could accurately predict the flooded area. To promote water management in the urban planning process, China formally announced a policy initiative to build a “sponge city” in 2014, which aimed to solve the problems of urban drainage and rainwater management. It was hoped that cities could be as resilient as sponges in adapting to environmental changes and coping with natural disasters caused by rain (Chen et al. 2021; Jiang et al. 2017). Wang et al. (2019b) built a Sponge City Flood Simulation and Forecasting System based on the concept of a “Sponge City”. This system contained a 3D icons “drag-and-drop” module, a design analysis module, a 3D stereo panorama module, a “storyboards” module, and an online shared view module (Table 2). The main focus of these modules was on the interface interaction, interface usability, and identification of visualization types. The geographic information system (GIS) could be used to operate and store visualization spatial and nonspatial data. It could be combined with hydrological models to better complete scenario analysis and optimization tasks. To enable users to experience the spatial sense more deeply, Huang et al. (2006) developed a GIS-based 3D visual simulation system for flood protection (Table 2). It was better to analyse and interact with of spatial data. The system adopted a client–server and browser-server architecture, including a relational database management system, a geographic information system, an expert system, a real-time data monitoring system, a user interface, and a model server. It was an exceedingly useful tool for the formulation and management of the flood policy. The sponge city flood simulation and forecasting system simulated the water accumulation process in some typical residential areas in Xixian New District, the first batch of China’s sponge city construction pilot cities. The experimental results showed that not only was the location of the simulated stagnant water is consistent with the location of the urban flooding but also the degree of stagnant water at each point was similar to the measured data. The average relative error between the accumulated stagnant area and the depth of the reservoir was 3.44% and 16.49%, respectively. Therefore, the simulated urban water accumulation process is consistent with the actual monitoring data. Zhang et al. (2009) created a flood control digital simulation platform based on flood control mathematical models, databases, and three-dimensional virtual reality technology, which considerably improved the comprehensiveness of information integration and the intuitiveness of the display of the flood control system on the overall

level. Intricate water resources and environmental conditions could be described by numerical models, which are important in river basin management and decision-making. Zhang et al. (2013) developed another virtual environment (VE)-based real-time interactive simulation framework in 2013 (Table 2). In the Dujiangyan project in China, this framework played an important role in the realization of its simulation and management. The framework was principally composed of two components: a virtual reality platform and a numerical model. The virtual reality platform had functions to control the simulation process and display data, and it was the master of the framework. The numerical model was responsible for the simulation of different types of events. This framework implemented interactive simulation and dynamic visualization based on the virtual environment.

Scientific prevention of flood disasters and the protection and utilization of local water resources are highly important for ecological development. Spatiotemporal data can suitably respond to the quantity and quality, spatial structural relationships, and changes over time of geographic elements because of has three characteristics, including spatial dimension, attribute dimension, and temporal dimension (Wang et al. 2017). Compared with previous two-dimensional (2D) and 3D GIS, the spatiotemporal GIS has prodigious advantages in visualization and spatial analyses (Hu et al. 2019b; Lienert et al. 2009; Wang et al. 2019a), which facilitate the representation of spatiotemporal changes in floods. Wu et al. (2019) used the digital earth platform as an engine to establish a dynamic visual simulation and decision support system for flood risk management (Table 2). The system mainly included data management, data query, model calculation, flood process simulation, visual decision-making and other modules. It could visually display the changes in a flood inundation range over time and provide decision-making support with scientific value for emergency management when floods truly came. The platform used Xiashan Reservoir, the largest reservoir in Shandong Province, as the research area and established the dynamic visualization simulation system of the flood risk of the Xiashan reservoir. According to the system data and input parameters provided by users, the changes in flood velocity and submergence time in the process of flood discharge in the upstream and downstream channels of the Xiashan reservoir could be calculated. The hydrodynamic model of the system was verified by comparing the calculated water level with the measured data of seven typical sections at different designed flood frequencies. The results showed that the calculated value of the hydrodynamic model was in agreement with the measured data under the condition of set water flow. This showed that the system could well simulate the flow dynamics of the downstream channel of the Xiashan reservoir well by establishing a suitable hydrodynamic model. According to the concept of interlinked resources, Ding et al. (2014) constructed a comprehensive environmental simulation framework for flood disaster management in virtual geographic environments (Table 2). In addition, they designed a prototype system on this basis. The system could be divided into six modules: Geo-database, Geo-computing module, Dynamic visualization module, Geo-model base, Geo-simulation module, and Geo-processing module. Their respective functions were to manage and store data, provide model-demand input, give spatial and analytical computational support for geo-simulation modules, present flood-related scenarios, offer packaging and management of geo-models, input and filtrate dynamic observational data streams. The system had the advantage of shifting from a static data-driven mode to a dynamic data-driven simulation mode and achieved more flood-related disaster prevention and response. The prototype system used Shenzhen, a coastal city in China, as the research area to reconstruct the 2013 Shenzhen "8•30" catastrophic flood event. The prototype system could generate different flood scenarios in Shenzhen, and the real-time recording frame rate was approximately 46

to 52 frames per second. These scenarios qualitatively revealed the evolution of floods and simultaneously provided very intuitive and fast information for monitoring and early warning, regional damage assessment, and decision support.

5.1.3 Simulation training systems suitable for earthquake hazards

An earthquake is a typical sudden natural disaster. In the last few years, there have been several major earthquake disasters, causing massive human casualties and economic losses worldwide. Therefore, only by increasing the public's awareness and response to earthquake disasters can earthquake risks and losses be reduced.

Safety training and education are crucial ways to reduce the number of casualties caused by earthquakes. Currently, traditional methods used to improve earthquake protection capabilities include evacuation exercises (Mitsuhara et al. 2015), watching tutorial videos, and reading safety manuals (Grant 2013). However, these traditional methods are tedious and difficult to simulate real emergency situations, and participants cannot experience more realistic evacuation scenarios. Therefore, Liang et al. (2018) designed a VR-based training prototype system, which mainly included some essential modules for earthquake scenario simulation, damage representation, interaction, player investigation and feedback. The system utilized HTC Vive as a Head Mount Display (HMD) device, which not only provided participants with a highly immersive experience but also enabled them to interact naturally and intuitively with the objects in the simulated earthquake scenario. This system also used Unity 3D's physics engine to simulate the physical effects of moving furniture and falling objects. Moreover, it used the virtual reality engine's particle system (the most successful modelling method in simulating irregular dynamic objects such as rain and snow) to simulate fire and smoke, which restored the real situation to a great extent. In addition, this prototype system based on virtual reality supplied effective feedback and evaluation to participants of evacuation drills (Table 3). Forty college student volunteers (20 males and 20 females) participated in the experimental study. The volunteers were divided into two groups, and each group consisted of 10 men and 10 women. The first group acted as a control group to learn safety knowledge with the help of traditional earthquake materials, and the second group acted as an experimental group to receive training using the prototype system. After the two teams learned the same time, they both tested the two parts of earthquake safety knowledge and the VR prototype exercise. Finally, experienced teachers judged the performance of each group. By comparing the performance of the two groups, the results indicated that the average value of the experimental group was considerably higher than that of the control group. Therefore, compared to traditional education methods, prototype systems could better improve the effectiveness of earthquake safety training. Wang (2012) proposed an urban earthquake damage prediction virtual simulation system. The structure of this system can be parted into four layers: data layer, support layer, functional layer, and application layer. The data layer provides the system with data support related to various earthquake disasters. The support layer provides two types of access interfaces for read–write and equipment. The functional layer is the integration area of different functional types of modules. The application layer mainly realizes the functions of different modules in the functional layer. This urban earthquake damage prediction virtual simulation system has an important role in promoting urban disaster reduction plans, emergency pre-plan compiling, and disaster control education. However, this virtual simulation system requires an expensive investment, which can make such training inaccessible to the public in less developed areas (Table 3). Therefore, Gong et al. (2015) provided a portable

Table 3 Summarize the characteristics of the simulation training system suitable for earthquake hazards

Name of systems	Advantages	Disadvantages	References
VR-based training prototype system	User responses can be identified; Provide experimental controls	Lack of physical simulation; Can't perceive shaking effect; Can't observe their own postures in the virtual scene	Liang et al. (2018)
Urban earthquake damage prediction virtual simulation system	Complete database structure; Simulation model reliable; Rich and vivid three-dimensional space	High system cost	Wang (2012)
Earthquake drill simulation system based on virtual reality	Portable and easy to deploy; Suitable for less developed areas	Motion sensor direction is not accurate; Poor speed control	Gong et al. (2015)
Earthquake simulator on a smartphone	Sensors equipped with external systems increase the reality of the scene	None noted	Yamamoto and Mizuno (2018)
Estimation system based on fast urban earthquake disaster simulation	Simulation process can be automated and accelerated	Not applicable to large cities	Fujita et al. (2014)

and cost-effective solution by designing a novel earthquake education system based on virtual reality. With the help of cloud computing technology and a commercial off-the-shelf (COTS) portable device, it was possible to provide users with a 3D immersive earthquake simulation environment. This new earthquake education system used SIGVerse, which was a client–server architecture simulation platform. It consisted of four parts: a simulation engine, a physical environment modelling, an earthquake power simulator, and a human–computer interaction module. Sixteen volunteers scored the system’s ease of use, model fidelity, control accuracy, and immersion through two simulation experiences before and after the earthquake in the undergraduate dormitory (5 points were excellent and 1 point was poor). The average score was approximately 4, indicating that the system could provide an immersive, easy-to-use environment for earthquake evacuation drills. Furthermore, the system had simulated earthquake scenarios on the simulation platform SIGVerse developed and designed by the National Institute of Information Technology of Japan. The user’s body could directly experience the simulated earthquake in real time. Simultaneously, the head-mounted display (HMD) delivered visual feedback to the user from a first-person perspective, which enabled the interaction between the body-sensing device and the simulation platform (Table 3). In addition to meeting the interaction needs of users through a dedicated virtual reality platform (Wang et al. 2019b), developing software on mobile devices would be the next breakthrough point. Takuma Yamamoto et al. (2018) developed a virtual earthquake simulator on smartphones based on the idea of attaching VR applications to VR goggles and implementing VR applications on smartphones. This enabled users to experience a highly realistic virtual earthquake in VR space using only smartphones and VR goggles. Due to its advantage of being easy to build, the system was valuable for schools and welfare agencies in organizing children to understand earthquake hazards (Table 3).

After an earthquake, a timely assessment of the extent of damage to the urban structure is of great importance to prepare various arrangements such as emergency personnel and resources. Fujita et al. (2014) developed a quick earthquake disaster estimation system. This system was composed of simulation and visualization modules. It used a combination of geospatial data and simulations to visualize the extent of urban damage. There was no doubt that this is particularly helpful to those responsible for earthquake disaster prevention and control (Table 3).

5.1.4 Simulation training systems suitable for a fire

A fire has the characteristics of sudden and destructive, threatening people’s lives and property. Most fire drills in the traditional sense are based on simulations at the visual and auditory levels, which lead to insufficient immersion, poor dynamics and interaction (Nahavandi et al. 2019; Yuan et al. 2012). The purpose of firefighting simulation training is not only to equip firefighters with proper firefighting skills and adequate training time but also to exercise them to take optimal actions in certain extremely dangerous environments (Nahavandi et al. 2019) to reduce injuries and property damage. Therefore, if we want to improve the experience of simulation training, it is necessary to simulate the establishment of a realistic fire environment (Williams-Bell et al. 2015; Yang et al. 2015). Recently, VR technology has been successfully applied in emergency training and education (Lee and El-Tawil 2007; Xu et al. 2020), and it can be combined with other simulation technologies to accomplish the creation of realistic fire environments.

Distributed interactive simulation (DIS) is an advanced simulation technology that can build a realistic virtual environment to achieve the effect of simulation exercises through computers, communication networks and VR (Li et al. 2004). Based on DIS and VR technologies, Li et al. (2004) came up with the concept of virtual collaboration of forest firefighting and designed a simulation system of collaborative forest firefighting. In this system, multiple users could share the same virtual environment. At the same time, after users enter the same simulation system, they could also communicate and collaborate to achieve real on-site effects. The architecture of the simulation system consisted of three parts, namely the system management unit, the firefighting unit, and the map view unit. The system management unit was responsible for the initialization of the firefighting drill, creating the virtual scene, calculating the fire spread time, and a replay and analysis after the event. It could be viewed as the controller of the entire fire simulation system. The map view unit and the system management unit shared the same processor, but they used various displays. To better show the spatial position of the fire scene and firefighting unit, it used a 2D map as the background and can exchange the location information and fire propagation information in real time with the map view unit. The firefighting unit was the place where the firefighters stand when they put out the fire. It had two firefighting modules, the ground and air firefighting units. The ground firefighting module was responsible for simulating the behaviour of vehicles or groups of vehicles, and the air firefighting module was responsible for simulating the process of aircraft firefighting. This two-tier firefighting unit design allowed the system to fully utilize the interaction between the behaviour of individuals or groups and the virtual environment. In addition, Nahavandi et al. (2019) from a better immersion perspective developed a VR immersive fire training simulator, called a portable firefighting training system. This system not only had a kinaesthetic feedback function to simulate the water (jet) reaction force ordinarily encountered during fire extinguishing but also used particle physics simulation to improve the realism of the interaction particles, such as water, fire and smoke. This system was composed of three main hardware components, namely a haptic hose, a branch or nozzle, and a compressed air breathing apparatus mask (or breathing apparatus system). It could intuitively complete firefighting control and real force feedback. Participants were asked to use fire nozzles and connected tactile hoses to extinguish a virtual fire while remaining standing. This practice is also called the pencilling drill in fire drills. To evaluate the effectiveness of the system, Nahavandi et al. asked six volunteers (four men and two women, with an average age of 36 years) to participate in the trial. Before the experiment, the experts demonstrated the pencilling drill and asked the volunteers to fill in a questionnaire to evaluate the difficulty of the pencil drill. After the test, the subjects still needed to answer two questions. Through subjective scoring of the subjects before and after the test, it was concluded that after using the system, the student's perception of the pencil exercise complexity was considerably improved ($p < 0.05$), which proved the usefulness of the system.

5.2 Response and recovery

5.2.1 Simulation training system based on fire evacuation

Emergency evacuation is critical in fire safety research. Investigations of building fire damage show that the successful evacuation of residents immediately after the fire starts can effectively reduce the number of casualties. The two main reasons for failing to evacuate people from burning buildings in time include: (1) the complex structural layout of the

building will extend the evacuation time and (2) residents will make unreasonable choices due to panic or unfamiliarity with the building. Through VR technology, security professionals and occupants are immersed in virtual building surroundings with virtual fire scenes. When they interact with the virtual environment and simulate the emergency evacuation, they can quickly determine the rationality of the architectural design and achieve the purpose of evacuation training and exercises. Ren et al. (2008) proposed a fire emergency evacuation simulation system, which consisted of six parts: a graphical user interface, an information management module, a fire simulation module, an emergency evacuation module, a firefighting simulation module, and a database. Among them, a virtual building with a “real” fire scene is provided to users by the fire simulation module. In the emergency evacuation simulation module, users can fulfil emergency evacuation drills and training. The user completes several elementary task trainings in the virtual situation of the fire simulation module, such as using a virtual foam fire extinguisher to put out a fire. The user can view the graphical user interface with the HMD when completing emergency evacuation drills and training.

5.2.2 Fire training system based on a post-earthquake fire

While the dry weather is known for easily causing fires, this common and dangerous secondary disaster also easily occurs after major earthquakes. Post-earthquake fires are one of the indirect disasters of earthquakes. The fires not only cause more serious economic and property losses than the earthquake itself in special environments or at time points (Hou and Li 2021; Li et al. 2019), but also cause firefighters and trapped people to face dangerous fires and suffer serious life threats. There are many factors that contribute to the phenomenon of a fire after an earthquake, which can be summarized in the following three aspects. First, water, electricity, gas pipelines, transportation systems, or communication systems become the causative factors for the occurrence and spread of a fire after being damaged by an earthquake. Second, damage to the sprinkler systems and water supply systems of buildings by an earthquake can have a lagging effect on the control and extinguishment of the initial fire. Third, after an earthquake, the fire protection coating or fire protection material of the building is extensively damaged, and thus, the buildings originally protected by fire protection materials will be directly exposed to the fire.

However, due to the complicated factors affecting a developing fire after an earthquake, people not only have little research on the construction of post-earthquake firefighting fire scenarios, but also do not have a deep understanding of the training system for post-earthquake fire rescue. Lu et al. (2020) proposed two aspects that need to be considered in the construction of VR scenes for fire and rescue after an earthquake. The first is to combine multiple dangers, such as structural or non-structural damage and fallen debris of buildings caused by earthquakes. The second one is smoke visualization. It is important to note that smoke visualization will affect the realism of visual effects due to differences in computer performance. Therefore, this can affect a range of behaviours of firefighters during evacuation and rescue. In summary, to create a relatively realistic post-earthquake fire environment, it is important to comprehensively consider, accurately and effectively simulating various factors. As a result of the above two aspects, Lu et al. (2020) proposed a simulation framework of an indoor post-earthquake fire rescue scenario. The framework is built on the basis of building information model (BIM) and VR. The simulation framework is composed of five modules, namely BIM, unity modelling, seismic damage assessment, post-earthquake fire simulation and virtual reality scene construction. The framework uses

the unity platform to model and visualizes post-earthquake fire scenes in 19-story hospital buildings and analyses the spread of fire and the flow of people in different scenes.

5.2.3 Urban lifeline-based simulation training system

The city's lifeline system is similar to the human blood system, which provides services for modern cities and ensures their ordinary operation in different aspects of energy, water, and communication (LauCELLi and Giustolisi 2015; Li et al. 2019). Once a link in the lifeline system falls into crisis due to catastrophic external events, the entire lifeline system is affected to varying degrees. Most lifeline facilities are buried underground. It is considerably intractable to identify and renovate the damage, which may cause long-term supply stagnation. Among the various kinds of natural disasters, earthquakes have the most vital and direct effect on the lifeline system (Choi et al. 2018). For example, the Northridge earthquake in California and the Kobe earthquake in Japan resulted in severe damage to the water supply network (Yoo et al. 2016). Therefore, it is highly imperative to predict the loss of lifeline infrastructure (Yoon et al. 2018).

As an important facility of the lifeline system, the water supply network not only provides residents with domestic water but also meets the needs of various urgent functions, such as firefighting and medical emergencies, during disasters (Tabucchi et al. 2010). Some tricky situations after an earthquake also causes an amplification effect due to the loss of the urgent service function of the water supply pipeline. Chang (2008) et al. constructed a water distribution network model based on virtual reality and used a software package to simulate it in a three-dimensional scene, which overcomes the limitations of traditional geographic information systems (Table 4). Chang et al. (2010) later used virtual reality technology to create an immersion scene simulation system of water distribution networks. The water network scene in the system could be updated at any time as the user operation changed in the field simulation. Compared with the traditional simulation system, the improvement was that the user could interact with the pipe network in the virtual simulation scene through the mouse, menu, and dialogue box. The user could actively obtain various information rather than be passive observers. This system visualized the massive amount of information in the water supply pipe network and provided a platform for the safety control of the urban water supply pipe network (Table 4).

The interdependence between the power system and the water supply system was considered the intermediate link of water energy (Khatavkar and Mays 2019). Han et al. (2016) designed a complex power grid collapse and restoration process simulation and deduction system, which became a simulation training tool for power grid analysts and enhanced the emergency handling capabilities of power grid company professionals. Based on the GIS platform and the intelligent power grid dispatching technology support system, the system completed the building of an interactive and distributed simulation supporting platform. The overall architecture of the application system had five layers: data layer, platform layer, application layer, application support layer, and user layer. Among them, the data layer mainly plays the role of storing various data. The platform layer achieves effective access to the data layer by providing primary services. The application support layer is the core program responsible for simulation and deduction. The user layer is designed based on different deduction scenarios to perform all user-level roles such as deduction commanders, dispatchers, and operators (Table 4).

Table 4 Summarize the characteristics of the urban lifeline-based simulation training system

Name of systems	Advantages	Disadvantages	References
Simulation system of urban water supply network based on virtual reality	Easily interact with application objects; Query real-time and historical data of application objects	None noted	Chang et al. (2008)
Interactive virtual scene simulation platform of urban water network	The interactive query is accurate (Node pressure, pipe section flow rate, and head loss)	None noted	Chang et al. (2010)
Complex power grid collapse and restoration process simulation and deduction system	Support multiplayer online deduction	None noted	Han et al. (2016)
Power emergency drill simulation system	The architecture model ensures the security and integrity of data information	The operation of constructing the virtual screen is more complicated	Huang et al. (2019)
Emergency functional recovery simulation focusing on the electric power supply system	Different types of emergencies can be simulated	The time to use the USGS server to retrieve seismic data is long	Hwang et al. (2016)

China's power grid is large and has a complex structure. Once affected by natural disasters, such as earthquakes, it remarkably causes the negative impact of large-scale blackouts. Power companies need to repair them in time. Shortening the time of power system failure will save economic and social benefits. Huang et al. (2019) created a power emergency simulation system aimed at promoting the professional skills and field response capabilities of emergency repair personnel. This system included the architecture combining Client/Server and Browser/Server, as well as formed four sub-modules based on three system buildings of hardware, software, and database. The four sub-modules were the drill configuration management module, the drill execution module, the single skill module, and the drill evaluation module (Table 4). Taking the emergency repair drill of 10 kV substation power as an example, after introducing virtual reality technology, the employees received emergency repair training. In the end, multiple departments completed emergency rescue drills while also improving the professional skills of their staff, which was of great importance for power maintenance and shortening the time of power outages. Hwang et al. (2016) developed an emergency functional recovery simulation model focusing on the power supply system to assess the damage caused by the power shortage after the earthquake and reduce the chaos in the disaster response process. The model included two modules for damage assessment of the electric power supply system and emergency operation/restoration analysis, which could provide the possible damage and response of the facility (Table 4).

5.2.4 Post-disaster emergency supplies preparation and dispatching simulation training system

After a major natural disaster, the related department of emergency management should send medical equipment, medicine, food, drinking water, clothes, quilts, and other materials to the disaster area as quickly as possible to reduce the problem of casualties or mass confusion (Kefan et al. 2014). Therefore, decision-makers must complete the inspection of the entire preparation and scheduling process of emergency supplies in a very short time (Jia and Kefan 2015), so that the supplies could reach the disaster area quickly and meet the needs of the people in the disaster area. Petri nets are modelling techniques mainly used for qualitative and quantitative analysis of workflow and workflow systems. Petri nets have good applicability in the optimization of workflows, and the main application in emergency management is the optimization of existing remedial rescue systems (Li et al. 2014b; Fanti et al. 2013). However, the application of Petri Net-based workflow systems in the preparation and scheduling of urgent aid was still relatively rare. Jia and Kefan (2015) established an emergency supply preparation and scheduling workflow simulation system based on the Petri net. Through this simulation system, decision-makers can discover the deficiencies in the entire emergency material preparation and scheduling simulation process and then make corresponding improvements. The Petri Net-based workflow system simulation solves the problem of optimizing the time used in the entire preparation and scheduling process (Moscatto et al. 2011; Yamaguchi et al. 2000).

Although the Petri network has solved some problems in the process of preparing for dispatching, some difficulties still need to be solved about the supply of emergency supplies. First, the spatial mismatch between supply and demand (Qiu et al. 2021) could affect the fairness and timeliness of emergency rescue (Wang and Sun 2018). Second, the rationality of priority setting is a decisive factor in allocating emergency resources (Jacobson et al. 2012), which could lead to different resource distribution schemes in the case

of different emergency conditions (Jiang and Yuan 2019). Determining a more reasonable priority (Donaldson and Mitton 2004) has become a problem faced by emergency works. Finally, vehicles responsible for transporting emergency supplies were affected by the dynamic disaster environment in route selection and scheduling, which made the implementation of emergency supply rescue operations very arduous. In summary, developing a cross-regional coordinated dispatch system and demonstrating the priority index (Jiang and Yuan 2019) that integrates the needs (Uddin and Huynh 2019) of material utilization, rescue equality, and distance of disaster sites (major disaster sites, minor disaster sites) has become an important development direction for future response to sudden natural disasters (Li et al. 2014a, b; Qiu et al. 2021).

Emergency food is an important material foundation for responding to emergency accidents, ensuring the basic lives of people in disaster-affected areas, and carrying out rescue work. The supply process of emergency food is the top priority of emergency supplies. Therefore, food emergency logistics have become a necessary part of the emergency rescue work. The grave damage of some critical infrastructures in the disaster area hindered the collection of emergency food in demand forecasting, vehicle and road selection and scheduling and caused safety problems, such as lack of quantity and quality of emergency food. Therefore, the development of emergency food dispatching decision-making and safe supply simulation training system with GIS, visualization, and other information technologies has become a research hot spot in the future.

In summary, there are few simulation training systems for natural disaster prevention and preparation, response, and recovery. To better compare the differences between relevant simulation training systems, the emergency phase, applicable disaster type, cause, conducting requirements, application, literature publication time, and other information of each simulation training system were summarized (Table 5).

6 Limitations of simulation training systems

As a promising technology, visualization technologies, such as VR and AR, have been widely used in simulation training systems. However, in terms of the practical application of simulation training systems, the simulation training process still has certain limitations and deficiencies in system equipment, user experience, evaluation functions, etc. Therefore, the current application range is not very wide. We briefly analyse the deficiencies in the application of most simulation training systems from the perspectives of hardware configuration requirements, user experience, evaluation functions and privacy protection, hoping to contribute to the improvement of the system (Alzahrani 2020).

6.1 High hardware configuration requirements

Hardware is a key factor that determines the training quality of the simulation training system (Chang et al. 2020). First, the relatively high cost of hardware is a major barrier. Due to the changeable scenarios and complex contents of seismic events, the details of the content that research and development personnel want to show when designing the background of simulation training are becoming increasingly complex. This requires the equipment to have powerful and rapid computing performance. In other words, the hardware facilities are required to have the ability to load large and complex models (Davila Delgado et al. 2020), as well as to have fast computing capabilities. Second, the fidelity of the simulator

Table 5 Comparison of relevant major natural disaster simulation training systems

Emergency phase	Type of disaster	Cause	Name of simulation training system	Conducting requirement		References
				Hardware	Graphics software	
Mitigation and Preparedness	Landslide	Landslides lead to complex disaster scenarios	Plugin-free browser/server (B/S) prototype system	Mouse	3D	Zhang et al. (2020)
	Flood	Heavy rainfall	Novel flood hazard warning system	CPU; video card	3D	Wang et al. (2016)
	Flood	Heavy rainfall or poor urban drainage	Sponge city flood simulation and forecasting system	Graphics card	3D	Wang et al. (2019b)
	Flood	Heavy rainfall	GIS-based 3D visual simulation system for flood protecting	OpenGL	3D	Huang et al. (2006)
	Flood	Heavy rainfall	VE-based real-time interactive simulation framework (VERTISF)	Mouse; Windows forms	osg GIS	Zhang et al. (2013)
	Flood	The rainfall and reservoir flood discharge	Dynamic visual simulation and decision support system for flood risk management	–	3D	Wu et al. (2019)
	Flood	Heavy rainfall	Integrated virtual geographic environmental simulation framework	–	3D	Ding et al. (2014)
	Earthquake	Residents need to be evacuated urgently after the earthquake	VR-based training prototype system	The hand controller; The Stereoscopic helmet	3D	Liang et al. (2018)
	Earthquake	Integral earthquake damage to urban engineering structures in different earthquake actions	Urban earthquake damage prediction virtual simulation system	–	3D	Wang (2012)

Table 5 (continued)

Emergency phase	Type of disaster	Cause	Name of simulation training system	Conducting requirement		A case study / Personnel training test	References
				Hardware	Graphics software		
	Earthquake	The violent vibration of an object during an earthquake	Earthquake drill simulation system based on virtual reality	Commercial off-the-shelf (COTS) portable devices; Head-mounted display	3D	Yes Sixteen volunteers conducted earthquake simulations in the dormitory building	Gong et al. (2015)
	Earthquake	The room vibrates strongly and objects such as furniture may fall	Earthquake simulator on a smartphone	Smartphon; VR goggles	3D	No	Yamamoto and Mizuno (2018)
	Earthquake	The earthquake caused the destruction of the urban structure	Estimation system based on fast urban earthquake disaster simulation	CPUs; memory	2D	No	Fujita et al. (2014)
	Forest fire	Forest fire spread	Simulation system of collaborative forest fire fighting	memory; graphics board	3D	No	Li et al. (2004)
	Fire	Firefighters urgently need to put out the fire quickly	Haptically-Enabled VR-Based Immersive Fire Fighting Training Simulator	HTC Vive; Haptic Hose; Branch or Nozzle; The compressed air breathing apparatus (CABA) mask; VR headsets	2D	Yes Six volunteers participated in the training trial	Nahavandi et al. (2019)
Response and Recovery	Fire	The crowd was not evacuated in time	Virtual reality system	Head-mounted display; Mouse	3D	No	Ren et al. (2008)
	Fire	Caused by an earthquake	Simulation framework of an indoor post-earthquake fire rescue scenario based on building information model (BIM) and virtual reality (VR)	Keyboard; Mouse	3D	Yes A 19-story hospital is chosen as the case study for a post-earthquake fire rescue	Lu et al. (2020)
	Earthquake	Complex topological structure of urban water supply network	Simulation system of urban water supply network based on virtual reality	-	3D	No	Chang et al. (2008)

Table 5 (continued)

Emergency phase	Type of disaster	Cause	Name of simulation training system	Conducting requirement		A case study / Personnel training test	References
				Hardware	Graphics software		
Earthquake	Complex urban water distribution network	Complex urban water distribution network	Interactive virtual scene simulation platform of urban water network	Mouse; CPU; Memory; Graphics card	3D	No	Chang et al. (2010)
Suitable for a variety of natural disasters	Large-scale power outages in the grid	Large-scale power outages in the grid	Complex power grid collapse and restoration process simulation and deduction system	-	-	No	Han et al. (2016)
Suitable for a variety of natural disasters	Electric power emergency repair	Electric power emergency repair	Power emergency drill simulation system	Computer; A sound image processing system; A sensing system	3D	Yes	Huang et al. (2019)
Earthquake	Power shortage after the earthquake	Power shortage after the earthquake	Emergency functional recovery simulation focusing on the electric power supply system	-	-	No	Hwang et al. (2016)
Suitable for a variety of natural disasters	Emergency supplies need to be prepared and dispatched	Emergency supplies need to be prepared and dispatched	Peiri Net-based workflow simulation system of the process	-	-	Yes	Jia and Kefan (2015)

plays a key role in narrowing the gap between real and simulation tasks. Fidelity here refers to the amount of details of the target environment are included in the simulation and how realistic these details are to be simulated (Doozandeh 2020). Therefore, the hardware system must be advanced to make the rendering of virtual scenes more realistic (Chang et al. 2020), which undoubtedly leads to higher costs. Third, the weight of the equipment has a great influence on the continuous wearing time of the students (Chang et al. 2020). Wearable devices (such as HMDs) are critical to the interaction between humans and training systems. Most of the wearable devices provided by some simulation training systems use rigid and bulky components, which not only restrict the natural free interaction with human soft bodies but also make users feel discomfort (such as neck pain and eye fatigue) after wearing them (Alzaharani 2020; Kim et al. 2020). When developers are researching wearable devices, they should focus on using lightweight materials to substantially reduce the weight of the device. Finally, the training platform of some simulation training systems lacks equipment that provides sensory and tactile feedback. By receiving and transmitting motion signals, haptic devices can enhance the real feelings of users and operators (Narciso et al. 2021). Most systems often only provide interactive images and sounds and lack perceptual feedback. To a certain extent, it limits the authenticity and reduces the overall training quality (Kim et al. 2020). Although some simulation training systems provide users with tactile feedback, the fidelity and stability of their rendering still need to be improved (Li et al. 2021; Xia et al. 2012). The reason why human beings can have coherent and smooth self-motion perception in three-dimensional space is usually obtained by relying on information from the vestibule, vision and proprioception. By effectively combining various sensory information, such as visual feedback and tactile feedback, the training performance of the system can be improved (Latham et al. 2019). Finally, the installation of system equipment also takes up much space (Wilson and Soranzo 2015).

6.2 Poor user experience

In addition to the hardware equipment factor, there is also a human factor that hinders the widespread application of the simulation training system (Yildirim 2019). Some users experience negative physiological reactions, such as eye fatigue, disorientation, nausea, headache, fatigue, drowsiness, and vomiting after experiencing the training of the simulation training system (Chang et al. 2020; Geršak et al. 2018; Palmisano et al. 2017). These are actually related diseases caused by the visualization technology used in the simulation training system, mainly including motion sickness and cybersickness (Bertolini and Straumann 2016). These uncomfortable feelings seriously damage the user's virtual reality experience and reduce the continuity of training (Lackner 1992; Llorach et al. 2014). Even if people are immersed in the same virtual reality content via the same devices, the physical discomfort symptoms vary from person to person (Chang et al. 2020). Therefore, individual differences are one of the reasons that affect virtual reality sickness (Dennison et al. 2016). The most common cause of virtual reality sickness is the sensory mismatch between the vestibular system and visual system (Kim et al. 2021). In addition, some literature works (Fulvio et al. 2021) claim that because of the small interpupillary distance in women, some head-mounted displays cannot make corresponding adjustments, which can cause eye fatigue and general discomfort. Some patients with underlying neurological diseases may be more susceptible to simulator disease, and sensory mismatch and postural instability are also potential reasons (Bos et al. 2008). In addition, some virtual reality devices also have a system delay defect. System delay refers to the lag between the

individual's sensing action and the system's final response to action (Wu et al. 2013). This increases the delay due to the increase in computing power and capacity. This causes a time mismatch between the user's eyes observing video image information and the user's body proprioceptor information (Geršak et al. 2018). Although some studies have focused on reducing these shortcomings as physical discomfort, the effect is not satisfactory. For example, some studies have shown that an increase in related types of diseases is closely correlated with an increase in the visual field the virtual environment, but expanding the visual field of the immersion device does not considerably improve virtual reality diseases (Chang et al. 2020). One strategy mentioned in the current literature to combat diseases associated with VR is dynamic field-of-view restriction, i.e. reducing the user's visual field to block peripheral visual motion in simulating self-motion (Teixeira and Palmisano 2020) or placing static frames and blur rotational movement on the virtual scene (Parsons 2021).

6.3 Lack of evaluation function and privacy protection

Most simulation training systems lack evaluation functions and cannot determine the achievement of skill acquisition. Professional guidance and evaluation feedback can help students better understand the corresponding skills. Some simulation training systems cannot give accurate and quantitative evaluations after the trainees' training operations. Therefore, the trainees cannot know whether their operations meet the basic requirements (Li et al. 2021). There is also a questionnaire survey before and after the training to determine the trainees' ability (Doozandeh 2020). Therefore, developers and designers should also consider the evaluation function after system training. In addition to the adverse effects of VR devices on the body or experience, there are doubts about whether virtual environments affect ethics and morality. In the Internet age, there is basically no secret about human behaviour, and more personal information is quietly collected. With the development and gradual improvement of visualization technology and simulation equipment, unique "kinematic fingerprint" information related to users' habits, movement patterns and behaviours may be captured, which may pose a threat to personal privacy in the future (Spiegel 2018). Therefore, corresponding privacy protection research is urgently needed to reduce privacy leakage.

7 Conclusion

This paper briefly describes the development of the simulation training system and its related visualization technologies, such as VR, AR, and MR. It mainly summarizes various simulation training systems and their system architectures and functions built for the four phases of natural disaster mitigation, preparedness, response, and recovery. These simulation training systems provide training tools for relevant personnel involved in emergency response, enhancing on-site response capabilities, and reducing the negative impact of common major natural disasters in the future.

At present, the world faces severe challenges that are difficult to predict and forecast for major natural disasters. The rapid development of computer technology provides a new way of thinking for disaster emergency management research. As emerging comprehensive computer technology, the research prospect of simulation training systems in the field of disaster emergency management has been highly valued by various countries. It has multiple roles in enhancing training effectiveness, enriching training means and contents, and

enhancing the relevance of emergency training under different types of natural disasters. Its application prospects are very broad. In particular, the global pandemic, COVID-19, has led many countries to adopt lockdown measures, urging people to maintain social distancing and reduce gatherings and large-scale events, which has brought many challenges to the implementation of transregional or transnational emergency drills. However, the natural disaster simulation training system can not only improve training efficiency and enrich training methods and content but also solve the epidemic's restrictions on the movement and gathering of people. Thus, the application prospects are very broad. However, at present, most simulation training systems still have deficiencies in their application experience, which is worthy of further research and exploration.

Author contributions Ning Li contributed to conceptualization, investigation, supervision, visualization, writing—review and editing, Funding acquisition. Na Sun contributed to investigation, visualization, writing—original draft. Chunxia Cao contributed to visualization. Shike Hou contributed to conceptualization. Yanhua Gong contributed to conceptualization, writing—review and editing, supervision, funding acquisition. All authors have read and approved the final manuscript.

Funding This work was supported by grants from the Ministry of Science and Technology of China (National Key Research and Development Program of China, 2019YFC1606304), and the Scientific Research Translational Foundation of Wenzhou Safety (Emergency) Institute of Tianjin University (TJUWYY2022021).

Declarations

Conflict of interests The authors declare that they have no conflict of interest.

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